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PERFORMANCE OF SOLAR REFLECTORS WHEN APPLIED TO THE STORAGE OF CRYOGENIC PROPELLANTS IN SPACE

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ABSTRACT

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An analysis was performed to determine the effectiveness of solar reflectors (spectrally selective surfaces with $\alpha/\epsilon < 1.0$) in reducing the heat transfer through the insulation of cryogenic fuel tanks located in deep space. The analysis considered the effects of surface coatings with α/ϵ ratios varying from 0.1 to 1.0 when applied to the external surfaces of either bulk insulation or to multifoil insulation. Results were obtained in terms of the heat leak to two cryogenic propellants, liquid hydrogen and liquid oxygen, when stored at Mercury, Earth, and Mars orbital distances from the Sun.

The results show that, with sufficiently good insulation and low heat leaks to the propellant, the α/ϵ ratio is a reasonable criterion of merit for these coatings, but that at larger heat leaks consideration of ϵ (or α) is necessary. It was observed that selective finishes of $\alpha/\epsilon = 0.1$ on a given amount of bulk insulation material can reduce the heat leak to 40 to 55 percent of the heat leak obtained when gray finishes are considered. Or, for equivalent heat leaks, a reduction in bulk insulation material thickness of about one-half is possible with high quality selective finishes ($\alpha/\epsilon = 0.1$) as compared with flat reflectors. Larger benefits may be achieved from selective finishes painted on foils as the analysis shows heat leak may be reduced tenfold when surfaces having an α/ϵ ratio of 0.1 are compared with gray surfaces. Again, consideration of equivalent heat leaks indicates that the use of approximately 10 times fewer foils of emissivity 0.05 is possible when spectrally selective surfaces are employed.

The present state of the art in achieving such surfaces is also briefly reviewed.

AUTHOR

INTRODUCTION

Cryogenic propellant systems, in general, give higher specific impulses and greater rocket vehicle performances than do storable propellants. This is true for both chemical rockets, where, for example, hydrogen-oxygen has been selected for the upper stages of the Saturn vehicle and for nuclear-driven systems, where hydrogen is the only working fluid being considered. However, the equilibrium temperatures of space vehicles having black or gray surfaces are well above those that can be used for storing cryogenics even at a distance of several astronomical units from the Sun. Therefore, any mission that requires the storage in space of cryogenic propellants also requires a consideration of the rate at which propellants will be lost through vaporization and the types and amounts of insulation needed to keep these losses within bounds.

Smolak, Knoll, and Wallner (ref. 1) have made such a study for a space vehicle using various types and thicknesses of insulation. They show, for example, that the loss of liquid hydrogen can be kept low enough to permit a manned mission to Mars if sufficient numbers of thin low-emissivity foils are used. Low-density powders and multiple radiation shields, while yielding low loss rates if used in sufficient thickness or numbers, are less attractive. However, only gray external surfaces, that is, those having $\alpha/\epsilon = 1.0$, were considered in reference 1. Adelberg (ref. 2), Burry (ref. 3), and Hibbard (ref. 4) have shown that spectrally selective surfaces having $\alpha/\epsilon < 1.0$ can give equilibrium temperatures in sunlight that are well below those obtained with gray surfaces. These lower temperatures suggest that the use of selective finishes on insulated tanks might result in either reduced rates of vaporization loss or permit the use of lighter insulation with equal losses. Therefore, an analysis was made to determine the advantages of spectrally selective coatings ($\alpha/\epsilon < 1$) relative to gray surfaces.

While Smolak, et al., made overall heat balance estimates on a realistic configuration exposed to solar radiation, Earth albedo, and Earth light, the absorption of solar radiation is by far the most important and is the only factor to consider in interplanetary flight. The present study was limited to plane insulated surfaces normal to the Sun, and results are given in terms of the heat leak to two cryogenic propellants of current interest, hydrogen and oxygen, when stored at Mercury, Earth, and Mars orbital distances from the Sun.

PROCEDURE

Opaque solar reflectors were considered to be applied to the external surfaces of two of the types of insulation studied in reference 1, that is, bulk insulation materials and closely spaced reflective surfaces (foils). These two types of insulation were examined because of their differences in modes of heat transfer. The heat leak through the bulk insulation was assumed to be entirely by conduction and, through the foils, entirely by radiation. Probably neither type of insulation actually transfers heat purely by one mode. However, calculations were made only for these ideal limiting cases. In both cases, only heat inputs from the Sun normal to the surface characterized by an α/ϵ ratio of 1.0 or less were considered.

If C is the solar flux in terms of power per unit area and α is the surface absorptance to this flux, the heat absorbed per unit surface area is $C\alpha$; the balance of the flux is reflected away. At equilibrium, the heat absorbed by the surface minus that reradiated to space is equal to the heat leak through the insulation. The heat balance for bulk insulation with heat transfer only by conduction may be expressed by the following equation:

$$C\alpha - \epsilon\sigma T_1^4 = \frac{k}{x}(T_1 - T_2) \qquad (1)$$

where

C solar flux, w/cm^2

k thermal conductivity of insulation material, $w/(cm^2)(^oK)/cm$

T_1 external surface temperature, ^oK

T_2 internal sink temperature, ^oK

x thickness of insulation material, cm

α absorptance of external surface to solar radiation

ϵ total emittance of external surface

σ Stefan-Boltzmann constant, $w/(cm^2)(^oK^4)$

For multifoil systems, where the internal heat transfer is through radiation alone, the following equation was used:

$$C\alpha - \epsilon\sigma T_1^4 = \frac{\sigma\left(T_1^4 - T_2^4\right)}{(N + 1)\left(\frac{2}{\epsilon^*} - 1\right)}. \qquad (2a)$$

The symbolism is the same as in equation (1) plus

N number of foils placed between external surface and surface bounding sink

ϵ^* emittance (gray) of foils

The denominator of the third term in equation (2a) defines the quality of the insulation. It can be replaced by $z \equiv (N + 1)\left(\frac{2}{\epsilon^*} - 1\right)$, which is a function of the number and emittance of the foils, to give

$$C\alpha - \epsilon\sigma T_1^4 = \frac{\sigma\left(T_1^4 - T_2^4\right)}{z} \qquad (2b)$$

Solutions of equation (1) for T_1 were calculated by trial and error for assumed values of C, α and ϵ, k/x, and T_2. Values of T_1 in equation (2b) were obtained directly for varying values of C, α and ϵ, z, and T_2. Solutions of both equations were performed for: (1) C equal to 0.059, 0.135, and 0.92 w/cm^2 corresponding to the solar flux at the Mars, Earth, and Mercury orbital distances, (2) α/ϵ ranging from 0.1 to 1.0 and for ϵ ranging from 0.10 to 1.0, and (3) T_2 equal to 20° and 90° K corresponding approximately to the normal boiling points of hydrogen and oxygen. It is not necessary to consider the effects of conductance and thickness for bulk insulation separately, since the parameter k/x describes the overall quality of the insulating blanket. This parameter was varied from 10^{-5} to 10^{-7}. The parameter z was varied from 20 to 3000. These variations covered a range of heat leak from about 10^{-2} to 10^{-5} w/cm^2. Calculations were not performed to values of heat leak greater than 10^{-2} w/cm^2 because these heat leaks are prohibitively high for most storage applications (ref. 1). Calculations were not made for heat leaks less than 10^{-5} w/cm^2 because the data presented herein can be linearly extrapolated or easily calculated to lower values of heat leak. After T_1 was determined with equations (1) and (2b), the heat leak through the insulation in watts per square centimeter was calculated for many cases within the above ranges of independent variables. The α/ϵ ratio was the principal variable studied, since this is a measure of the spectral selectivity of the surface. The results of these calculations are presented in the following section.

RESULTS

Spectrally Selective Surfaces on Bulk Insulation Materials

Figure 1 presents the heat leak through bulk insulation materials against α/ϵ for parameters k/x and ϵ, for several orbital distances from the Sun, and for sink temperatures of 20° and 90° K. Figure 1 shows that the heat leak is always less for spectrally selective surfaces ($\alpha/\epsilon < 1$) than for black or gray surfaces ($\alpha/\epsilon = 1.0$).

In addition to the general effect that the heat leak always decreases with decreasing α/ϵ ratio, the independent effect of ϵ (or α) on the heat leak must be considered, since a given α/ϵ ratio can be achieved with different values of ϵ. For example, $\alpha/\epsilon = 0.5$ for both $\alpha = 0.25$, $\epsilon = 0.5$ and for $\alpha = 0.125$, $\epsilon = 0.25$.

The heat balance equations (1) and (2b), show that this independent effect will become less significant as the insulation quality improves or as the heat leak magnitude decreases. Consider the terms on the right side of equations (1) and (2b). As lower values of the variable k/x or higher values of variable z are assumed, the heat leak will eventually become negligible compared to the heat absorbed and reradiated by the coated surface. For this condition, equation (1) or (2b) may be written approximately as

$$T_1 \cong \left(\frac{C}{\sigma}\frac{\alpha}{\epsilon}\right)^{0.25} \tag{3}$$

The extent of this approximation may be observed, for example, from figure 1, where $C = 0.135$ w/cm^2 and $T_2 = 20^\circ$ K. For a relatively poor quality of insulation characterized by $k/x = 10^{-5}$ w/(cm^2)($^\circ$K) and the fairly substantial heat leaks shown, the calculations show the independent effect due to ϵ as indicated by the separate curves drawn for $\epsilon = 1.0$, 0.3, and 0.2. This effect diminishes as the quality of insulation improves so that at $k/x = 10^{-6}$ a narrow band, shown at low values of α/ϵ, describes all values of ϵ from 0.1 to 1.0. At $k/x = 10^{-7}$, a single curve can be drawn for these values of ϵ. In general, all the single-line approximations shown in figure 1 are correct to ±4 percent or better at $k/x = 10^{-6}$ and to ±1 percent or better at $k/x = 10^{-7}$. At $k/x = 10^{-7}$ or less, surface temperatures can be calculated for the range of values of ϵ considered by equation (3) with inaccuracies no greater than 1 percent.

As previously stated, the use of spectrally selective finishes on the surface of a given amount of bulk insulation material can reduce the heat leak by amounts that vary primarily with the α/ϵ ratio and only slightly with the individual values of α and ϵ. Selective finishes of $\alpha/\epsilon = 0.1$ reduce the heat leak to 40 to 55 percent of the values obtained with gray surfaces. The leak is also dependent on C, T_2, and k/x.

Spectral selectivity can also reduce the thickness of insulation required to keep the heat leak at a given value. This is shown in figure 2 where the heat leak at 1 A.U. is shown as a function of the thickness of a bulk insulation material having a thermal conductivity, k, of 1.44×10^{-6} w/(cm^2)($^\circ$K)/cm. This value of k is about the lowest achieved to date for this type of insulation (ref. 1). The curves in figure 2 are for α/ϵ ratios of 0.1 and 1.0 and for heat sinks of 20° and 90° K. This figure shows, for example, that if a heat leak of 5×10^{-5} w/cm^2 is permissible into a liquid hydrogen tank, then 10.8 in. of insulation is required with a gray surface and only 5.8 in. if a spectrally selective surface having $\alpha/\epsilon = 0.1$ is applied. In general, insulation thicknesses can be reduced by about one-half if surfaces having $\alpha/\epsilon = 0.1$ can be achieved.

Spectrally Selective Surfaces on Foils

Figure 3 presents the heat leak through foils against α/ϵ for parameters z and ϵ. The orbital distances from the Sun and sink temperatures are identical to those considered for bulk insulation materials. A comparison of heat leak through the foils at $\alpha/\epsilon = 0.1$ and 1.0 for all values of z shows that the leak can be decreased tenfold when spectrally selective surfaces are employed and that heat leak is almost invariant with sink temperatures between 20° and 90° K.

As in the case of "spectrally selective surfaces on bulk insulation materials," there is present the independent effect of ϵ (or α) and α/ϵ on the value of heat leak. As figure 3 shows, this effect is not significant for values of z equal to 100 or more. For values of z greater than 100, a single-line approximation of heat leak against α/ϵ over a range of $\epsilon = 0.1$ to 1.0 may be drawn. The accuracy is ±4 percent at $z = 100$ and ±1 percent at $z = 1000$ or lower.

At $z = 20$, figure 3 shows that the heat leak through foils is dependent on the values of both α/ϵ and ϵ for variable orbital distances from the Sun at the large values of heat leak considered.

Figure 4 shows the variation of heat leak with z for selective ($\alpha/\epsilon = 0.1$) and nonselective coatings on foils at 1 A.U. for the range of $\epsilon = 0.1$ to 1.0 and a sink temperature of 20° K. Also shown at the corresponding values of z are the number of foils required for an assumed foil emissivity (ϵ*) equal to 0.05. Figure 4 indicates that a selective surface characterized by $\alpha/\epsilon = 0.1$ will allow a tenfold decrease in z and approximately a tenfold decrease in the number of foils for equivalent heat leaks. This, in turn, will decrease the foil composite thickness approximately 10 times (ref. 1).

Practical considerations. - The data shown to this point have all been the results of purely analytical considerations and calculations and have shown the benefits that might be derived in coating tank surfaces with spectrally selective finishes; α/ϵ values between 0.1 and 1.0 have been used. This last section briefly summarizes the present state of the art in achieving selective surfaces with α/ϵ ratios below 1.0.

Spectrally selective surfaces have been and are now being used on space vehicles and components. Examples are the use of a silicon monoxide coating on the Vanguard and the use of glass, quartz, or sapphire covers on photovoltaic cells. In both cases, tolerable operating temperatures are achieved through the use of these materials.

It has long been known through both theory and experiment (refs. 5 and 6) that metals and semiconductors have higher spectral absorptivities at shorter wavelengths than at long and that the reverse is true for nonconductors. As a result the metals and semiconductors have α/ϵ ratios greater than unity and the nonconductors have ratios less than 1.0. The inorganic oxides are examples of nonconductors and should be effective in reducing the temperatures of space vehicles.

The α/ϵ ratios less than 1.0 must be attained through the use of coatings of nonconductors applied to metal substrates. These coatings can be applied through flame or plasma spraying with Rokide A being an example of flame sprayed aluminum oxide. An α/ϵ ratio of 0.35 has been measured for this material (ref. 7). Coatings are perhaps more easily applied through the use of oxide pigmented paints, and the common white paints have α/ϵ ratios less than 1.0. Since the organic vehicle of common paints is likely to degrade in the space environment, a completely inorganic paint using sodium silicate as the vehicle and Wollastinite (calcium silicate) as the pigment has been used. This surface coating has given an α/ϵ ratio of 0.17 (ref. 7).

In general, spectrally selective finishes having α/ϵ ratios of about 0.2 are available and are easily applied. The calculations herein show that coatings of this quality can reduce to about 60 percent the heat leak through a given thickness of good bulk insulation and reduce to about 20 percent the leak through a multifoil system as compared with gray surfaces ($\alpha/\epsilon = 1.0$). Or, as previously indicated, less insulation can be used for a given heat leak.

An even greater saving in heat leak is indicated if the above comparison is made between the available selective coatings and the practical metallic substrates on which the coatings are likely to be placed. The uncoated external surfaces of multifoil systems may be aluminum. Titanium, stainless steel, or aluminum may be used to cover and seal bulk insulation materials surrounding propellant tanks. Reference 8 lists values of $\alpha/\epsilon = 3.2$ for forged Al6061 chemically polished, $\alpha/\epsilon = 1.7$ for sand-blasted stainless 410, and $\alpha/\epsilon = 3.3$ for 6Al4VA titanium alloy. For purposes of a rough comparison, assume that $\alpha/\epsilon = 3.0$ is a reasonable value for these materials. Then, an approximate extrapolation of the results contained herein indicates that coatings of $\alpha/\epsilon = 0.2$ can reduce to about 45 percent the heat leak through bulk insulation sealed with the metal discussed or can reduce to about 7 percent the heat leak through a multifoil system.

The α/ϵ ratios of coated surfaces may be functions of the nature of the substrate, the pigment and vehicle used in the coating, the thickness of the coat, and its surface roughness. Considerable research is under way aimed at developing a better understanding of the effects of these variables and is searching for coatings with better spectral selectivity. Also a factor is the stability of the surface coating to the space environment. Reference 9 has shown the absorptivity of many oxides to increase and therefore the α/ϵ ratio to increase when exposed to sunlight. Much additional work is needed in this area.

CONCLUSIONS

The analysis has shown that the heat transfer through the insulation of cryogenic propellant tanks located in deep space can be substantially reduced when solar reflectors are applied to the external surface of the insulation. The comparison is made with the higher heat leak obtained when flat reflector coatings are used with identical insulation.

It was found that the heat leak into stored cryogenic hydrogen or oxygen varies primarily with the α/ϵ ratio and only slightly with the individual values of α or ϵ when sufficiently good insulation is used and low heat leaks are obtained. The heat leak is also dependent on the orbital storage distance from the Sun, the ratio of thermal conductivity to thickness of bulk insulation, or the number of foils and their internal emissivity.

Currently available spectrally selective coatings painted on the external surfaces of insulation materials can reduce to about 60 percent the heat leak through good bulk insulation and to about 20 percent the heat leak through a multifoil system when the leaks are compared with those obtained with flat reflector paints or insulation.

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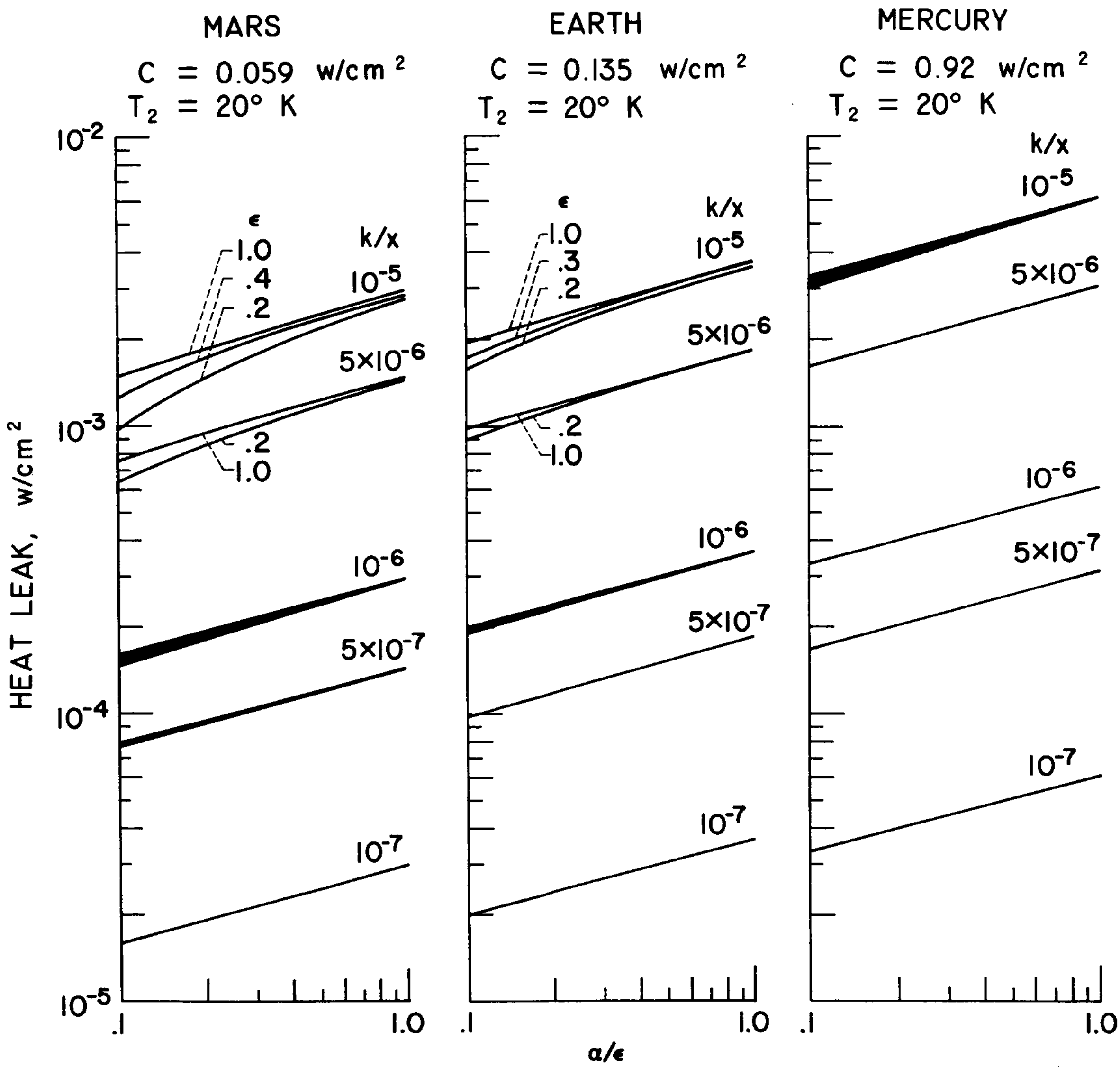

Figure 1. - Heat leak through bulk insulation against α/ϵ.

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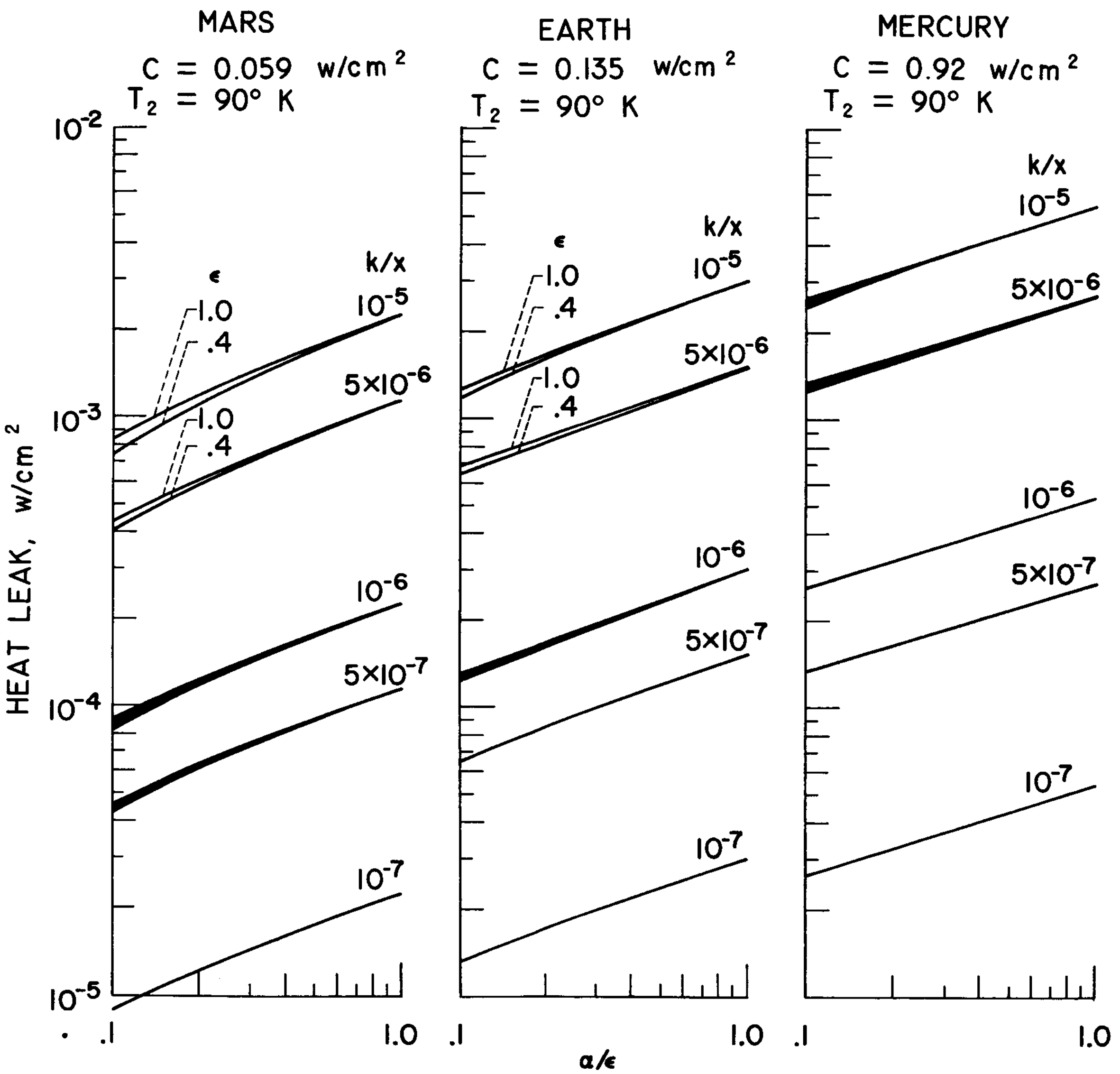

Figure 1. - Concluded. Heat leak through bulk insulation against α/ϵ.

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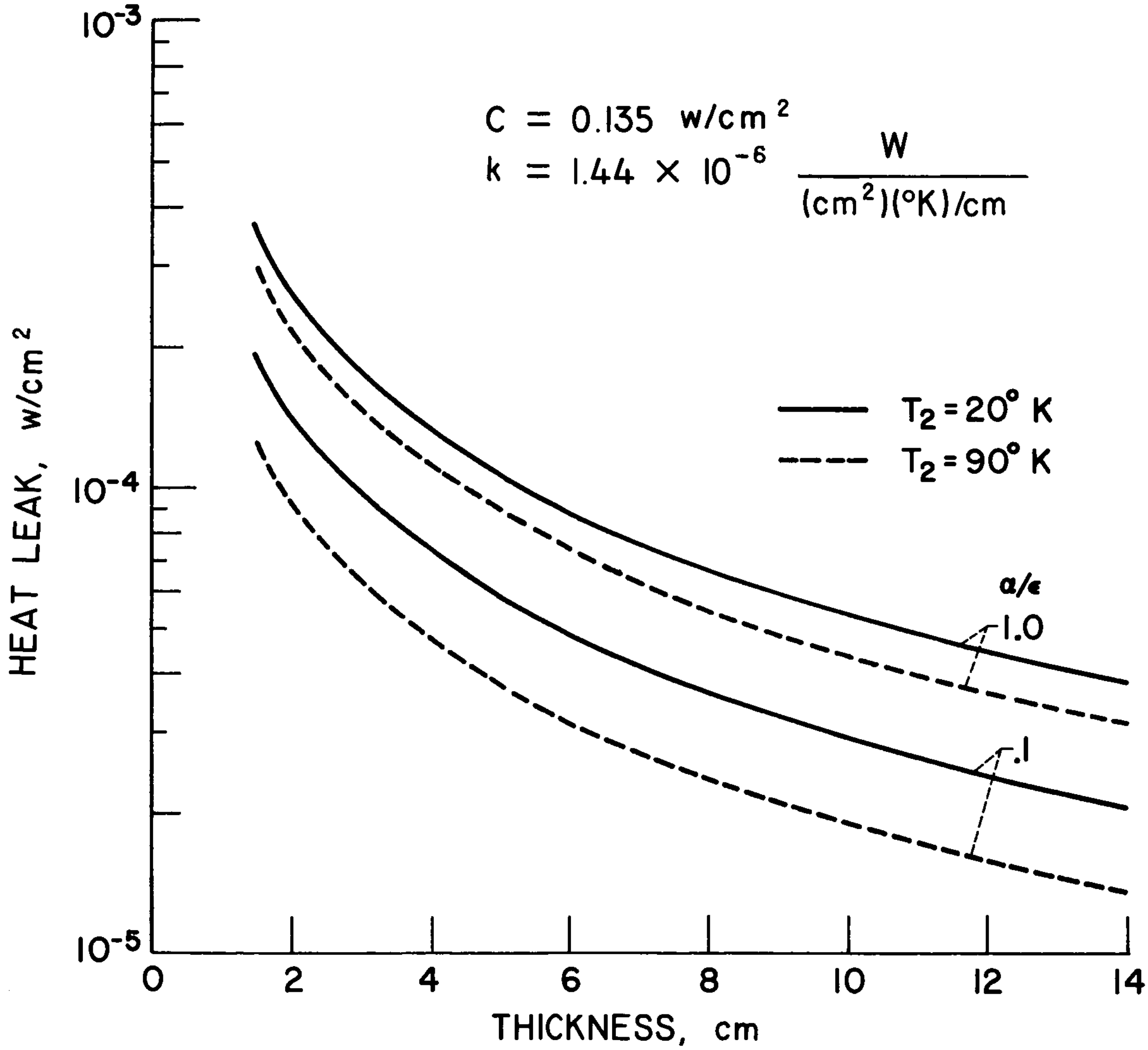

Figure 2. - Heat leak against bulk insulation thickness for selective and gray coatings.

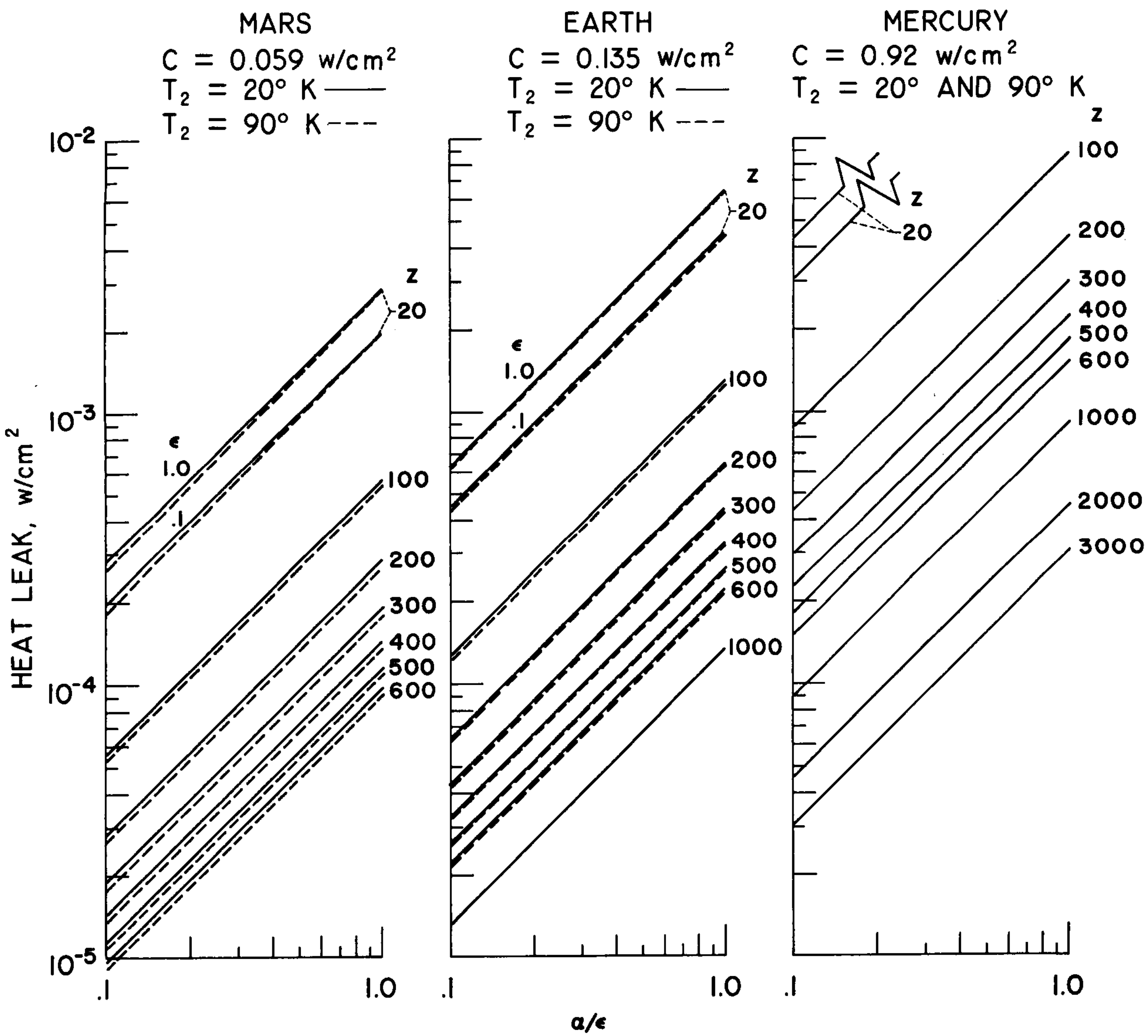

Figure 3. - Heat leak through foils against α/ϵ.

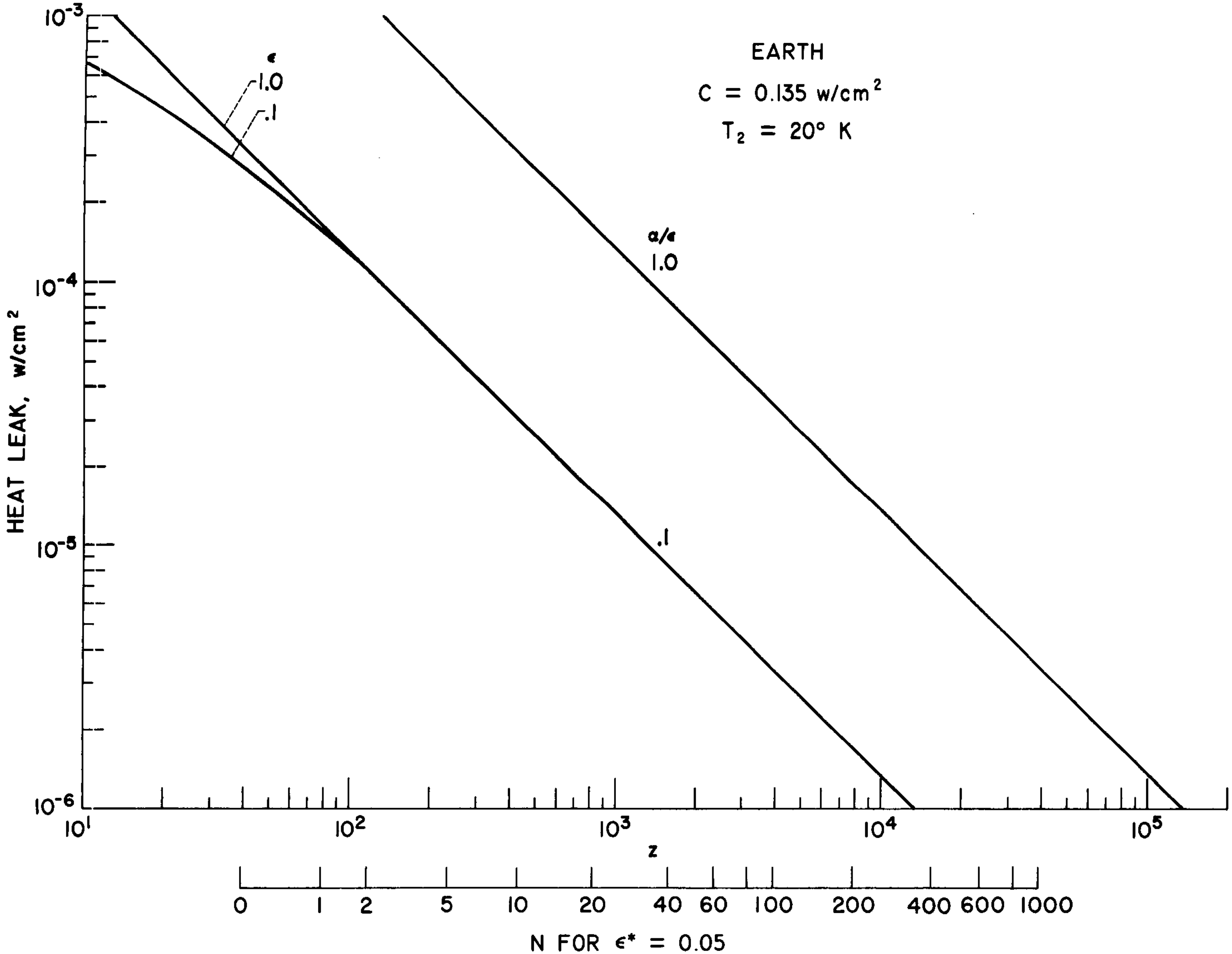

Figure 4. - Heat leak against z and number of foils for selective and gray coatings.